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# Scalar WIMP Dark Matter at the LHC

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Based on [arXiv:0909.3094], [arXiv:1005.0090]

# Scalar WIMPs from Inert Doublets

A wide variety of BSM scenarios predict the presence of additional scalar SU(2) doublets, beyond the single Higgs doublet of the SM.

Such doublets are often “inert” in the sense that they receive no VEVs and have no Yukawa couplings with SM fermions.

The minimal “Inert Doublet Model” includes:

(Deshpande, Ma 1978; Ma 2006; Barbieri, Hall, Rychkov 2006; and others)

- $\phi_1$  : SM Higgs doublet ( $\langle\phi_1\rangle = v/\sqrt{2} = 174$  GeV).
- $\phi_2$  : The inert doublet ( $\langle\phi_2\rangle = 0$ )
- There exists an **unbroken**  $\mathbb{Z}_2$  parity under which:

Even

$$\phi_1 \rightarrow \phi_1 \quad f_{SM} \rightarrow f_{SM} \quad V_{SM}^\mu \rightarrow V_{SM}^\mu$$

Odd

$$\phi_2 \rightarrow -\phi_2$$

# Why would one want an Inert Doublet?

Such doublets have a host of phenomenological applications:

- **A promising dark matter candidate: the “LIP”**  
(Barbieri, Hall, Rychkov 2006; Honorez, Nezri, Oliver, Tytgat 2007; Gustafsson, Lindström, Bergström, Edsjö 2007; Dolle, Su, 2009; et al.)
- **Oblique S and T Contributions from an inert doublet allow for a heavy (400-600 GeV) Higgs.**  
(Barbieri, Hall, Rychkov 2006)
- **A connection to neutrino physics**  
(Deshpande, Ma, 1978; Ma 2006; Agrawal, Dolle, Krenke 2008)
- **Triggering Electroweak symmetry-breaking**  
(Hambye, Tytgat 2007)
- **And much more...**

# Parameter Space of the Model

$$V = \mu_1^2 |\phi_1|^2 + \mu_2^2 |\phi_2|^2 + \lambda_1 |\phi_1|^4 + \lambda_2 |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 |\phi_1^\dagger \phi_2|^2 + \lambda_5 [(\phi_1^\dagger \phi_2)^2 + h.c.]$$

$$\phi_1 = \begin{pmatrix} 0 \\ (v + h)/\sqrt{2} \end{pmatrix}$$

$$\phi_2 = \begin{pmatrix} H^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$$

Physical Scalars

Take S to be the LIP:

$$m_S < m_A, m_{H^\pm}$$

Mass Splittings:

$$\delta_1 \equiv m_{H^\pm} - m_S = -\frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

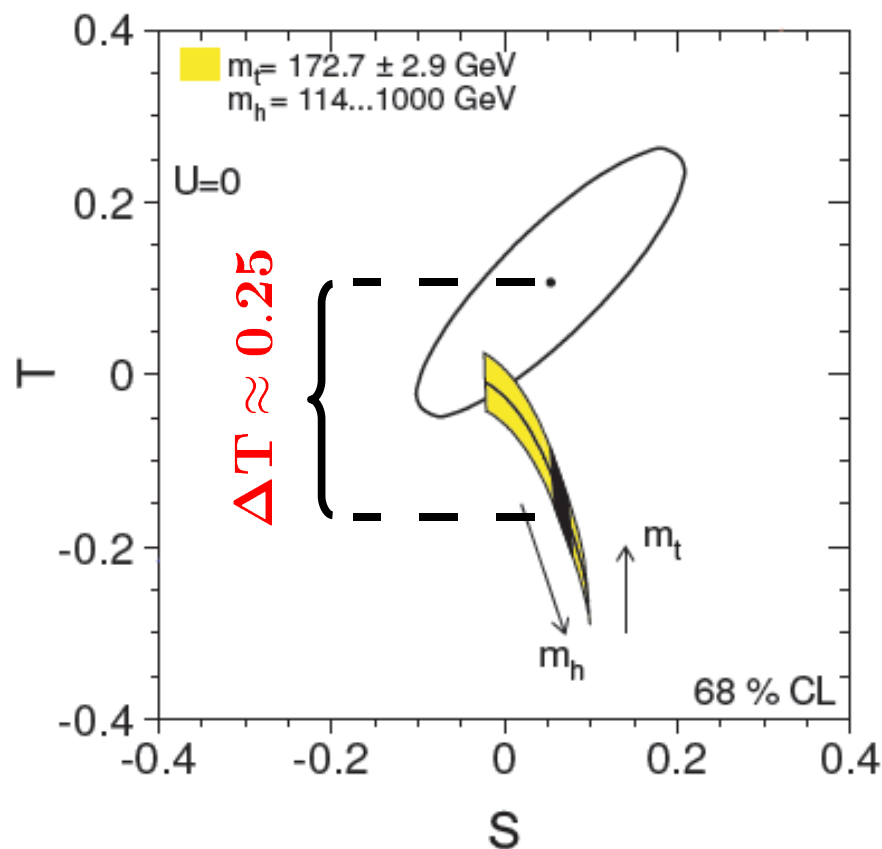
$$\delta_2 \equiv m_A - m_S = -\lambda_5 v^2$$

Also useful to define:  $\lambda_L \equiv \lambda_3 + \lambda_4 + \lambda_5$

(Represents physical  $hSS$  coupling)

# Accommodating a Heavy Higgs

An inert doublet provides a way of circumventing LEP bounds on the Higgs mass: (Barbieri, Hall, Rychkov 2006)



- Additional scalars can provide a positive contribution to the  $T$  parameter:  
(Peskin, Wells 2001)
- In the IDM, this contribution is:

$$\Delta T \approx \frac{1}{24\pi^2\alpha v^2} \delta_1 \delta_2$$

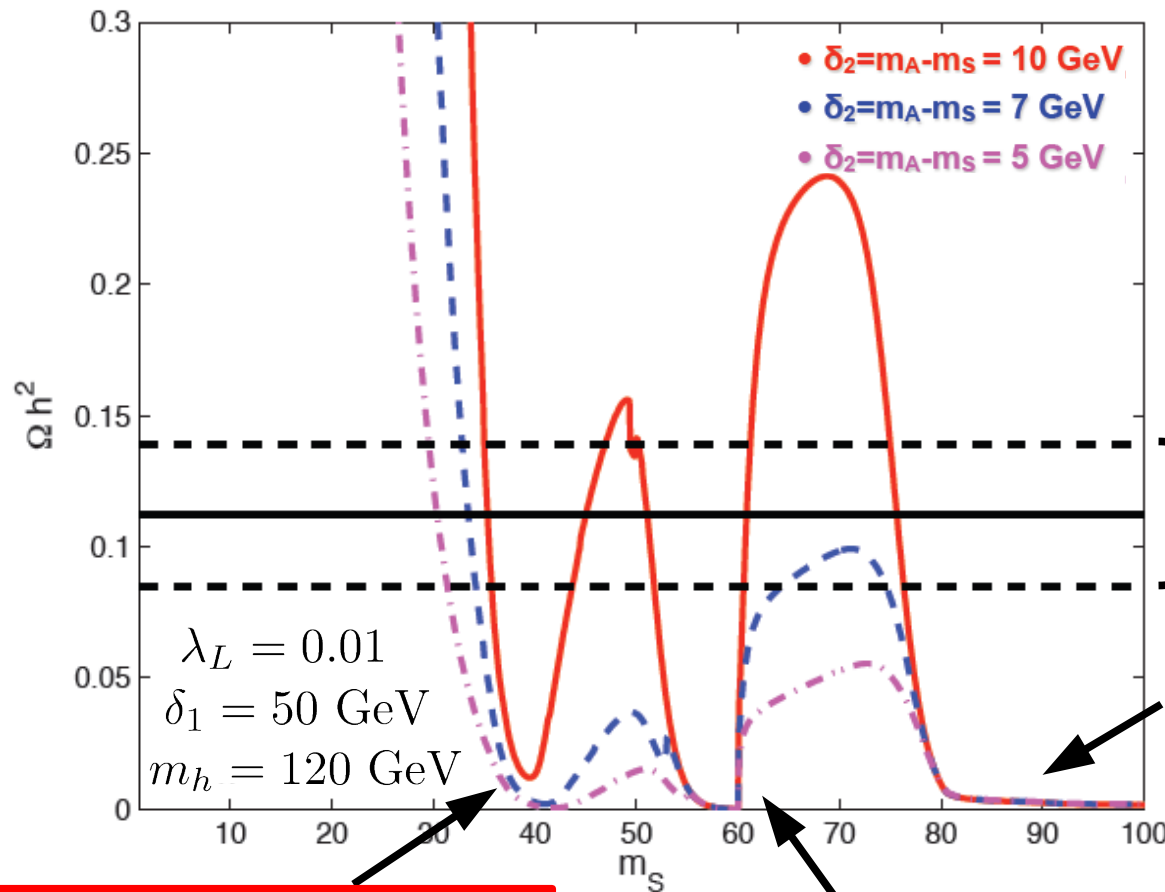
So if...

$$90 \text{ GeV} < \sqrt{\delta_1 \delta_2} < 140 \text{ GeV}$$

... the IDM can compensate for a heavy Higgs!

(figure: <http://lepewwg.web.cern.ch/LEPEWWG/>)

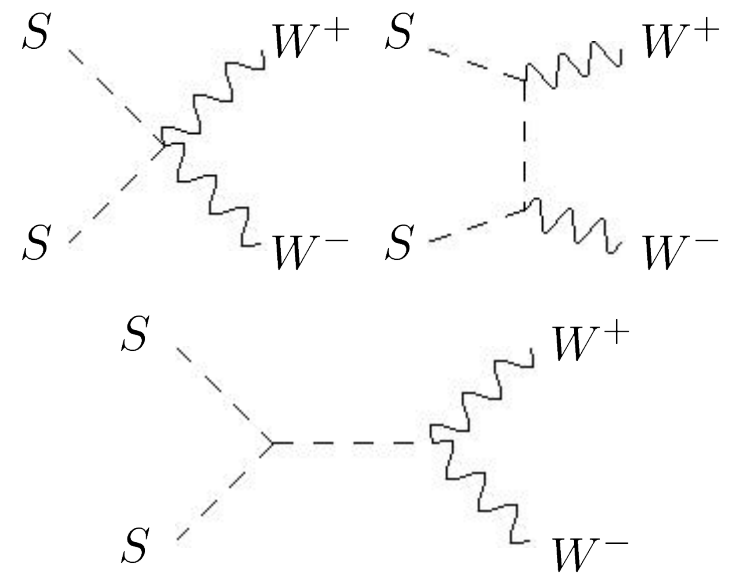
# LIP Dark Matter



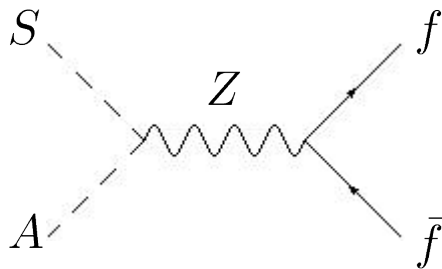
- The stable LIP is a good WIMP dark matter candidate. It annihilates primarily through an  $h$  or  $Z$  resonance when light, and into  $W^+W^-$  when  $m_S > M_W$ .

WMAP-Allowed Region

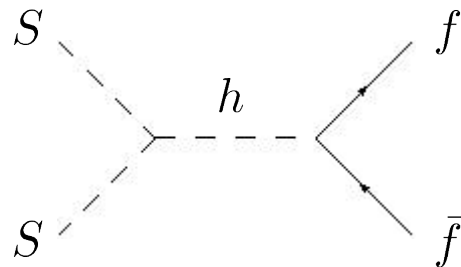
$SS \rightarrow W^+W^-$  annihilation:



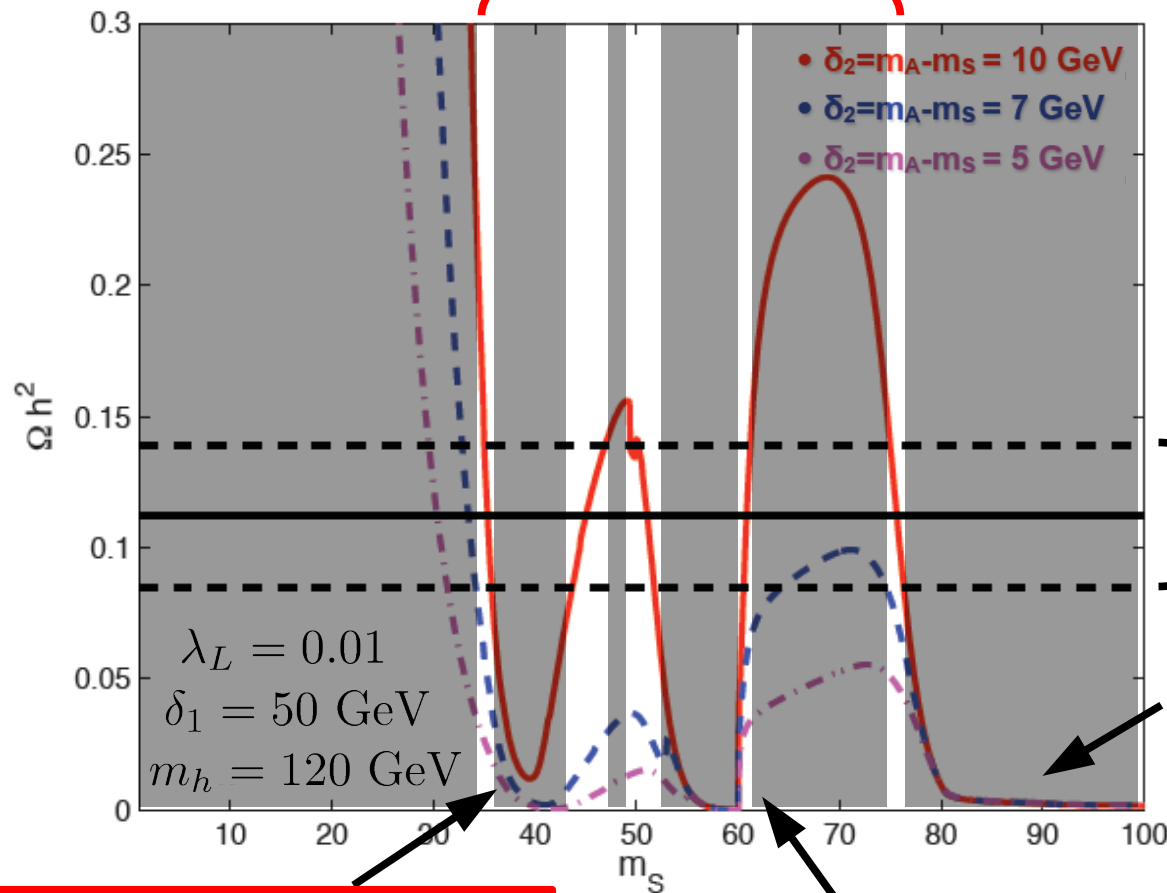
Z-pole annihilation:



$h$ -pole annihilation:



Bands:  $\Omega_{\text{DM}}$  within WMAP  $3\sigma$  range

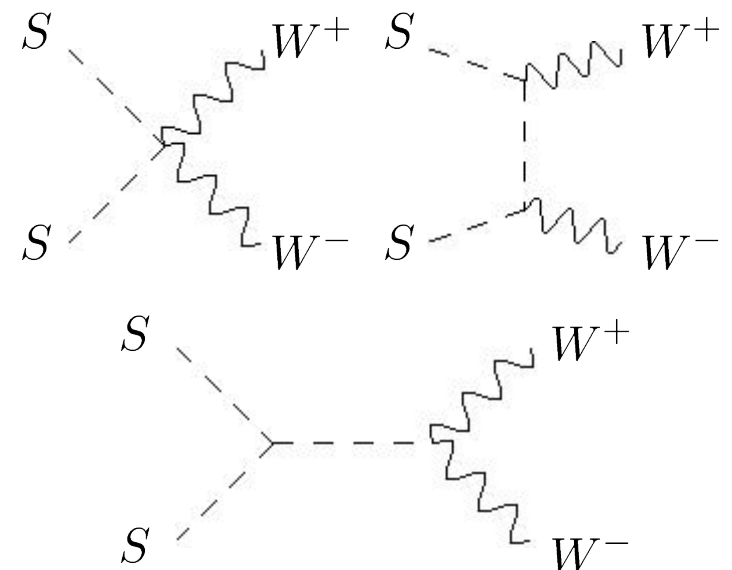


## LIP Dark Matter

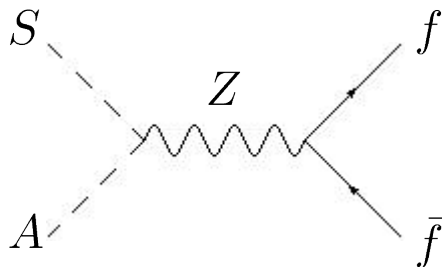
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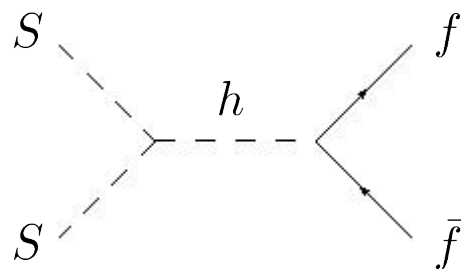
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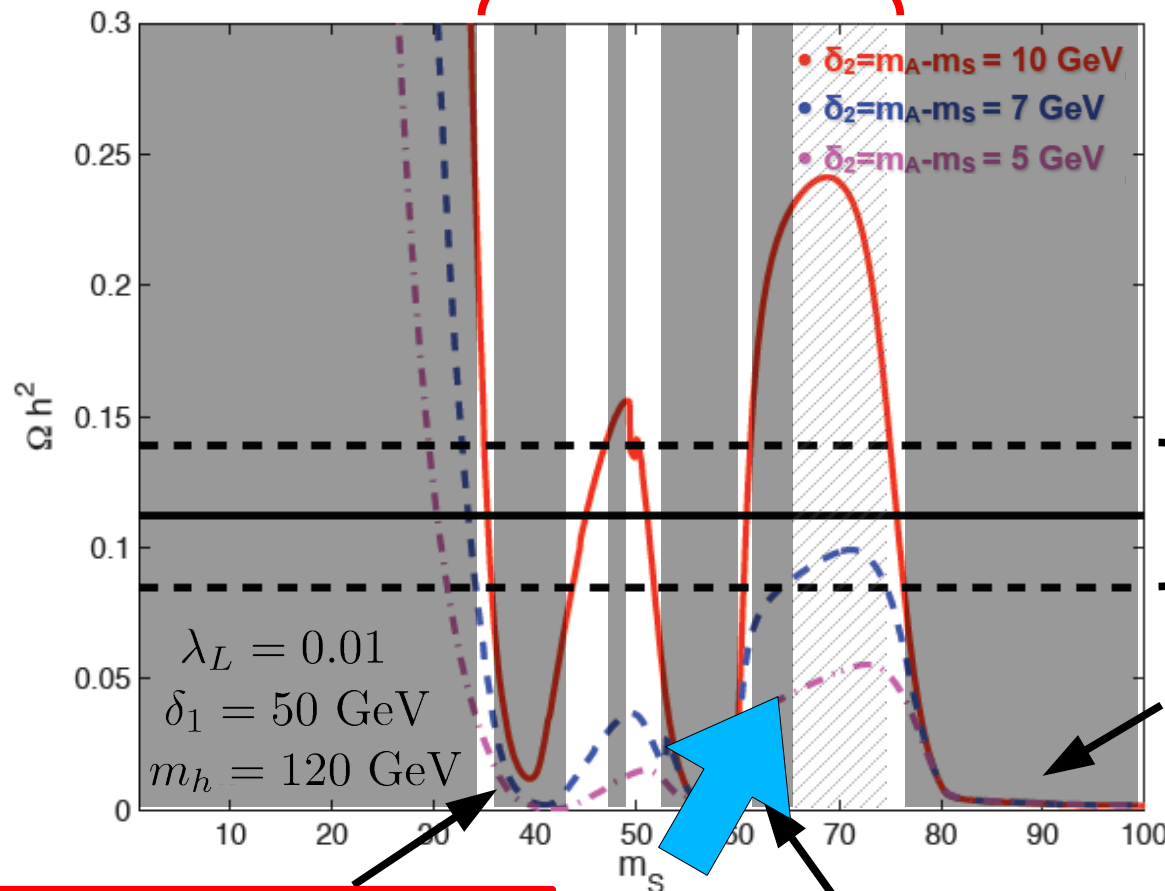


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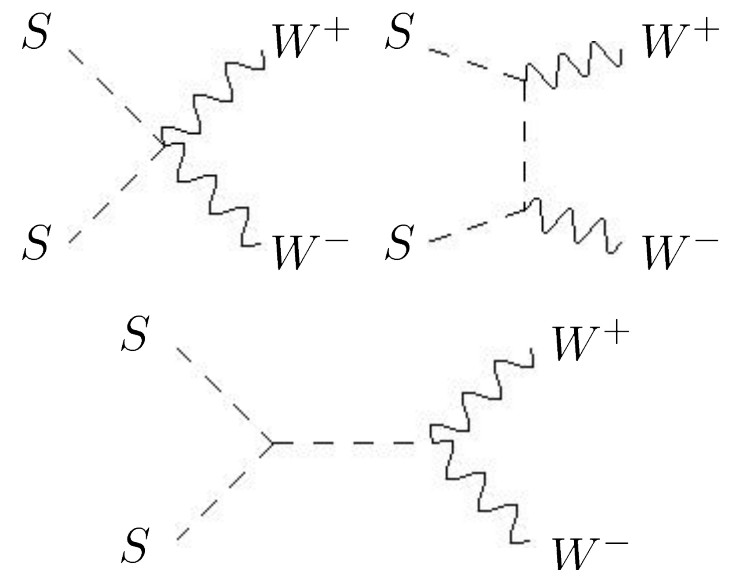


## LIP Dark Matter

- The stable LIP is a good WIMP dark matter candidate. It annihilates primarily through an  $h$  or  $Z$  resonance when light, and into  $W^+W^-$  when  $m_S > M_W$ .

WMAP-Allowed Region

$SS \rightarrow W^+W^-$  annihilation:



And things may even be a little bit better...

Including three-body contributions from  $SS \rightarrow WW^*$  decay can increase annihilation efficiency in cases where  $m_S \sim m_W$  (Lopez Honorez, Yaguna 2010).



# Constraints on the IDM

## Consistency Conditions

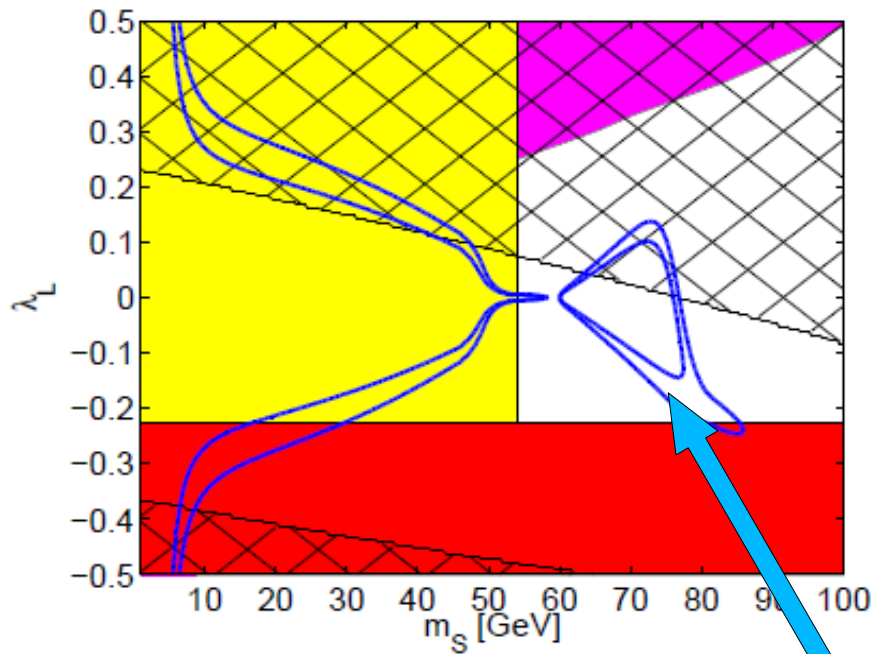
- Vacuum Stability
- Perturbativity

## Experimental Constraints

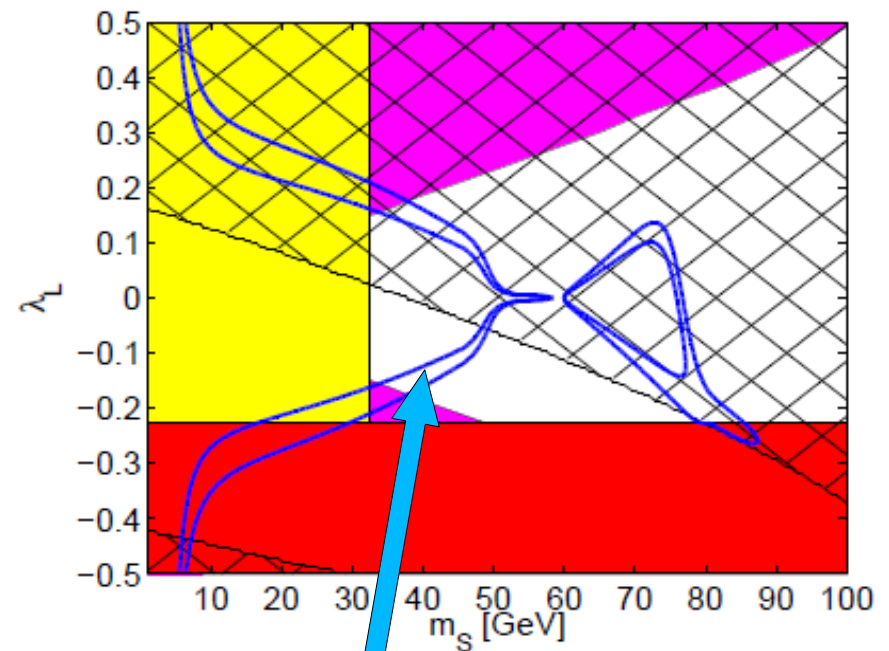
- Dark matter relic abundance (WMAP)
- Precision electroweak constraints (LEP)
- BSM Searches (LEP)
- Direct detection bounds (CDMS, etc.)

# Combined Constraints: Light Higgs

$$\{m_h, \delta_1, \delta_2\} = \{120, 50, 50\} \text{ GeV}$$



$$\{m_h, \delta_1, \delta_2\} = \{120, 70, 70\} \text{ GeV}$$



- Direct detection limits
- LEP direct searches
- Vacuum stability
- Perturbativity
- DM relic density

Light LIP:  
 $m_s \sim 60 - 80 \text{ GeV}$

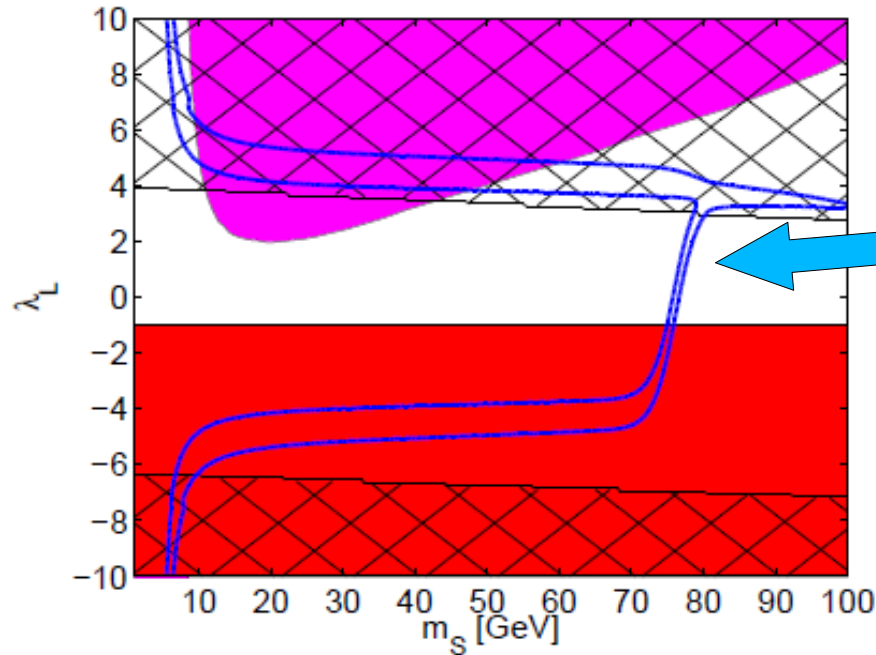
**Very** light LIP:  
 $m_s \sim 40 \text{ GeV}$

- Applying the combined constraints, we find a set of consistent scenarios in which the LIP accounts for the observed DM abundance.






# Combined Constraints: Heavy Higgs

$$\{m_h, \delta_1, \delta_2\} = \{500, 250, 110\} \text{ GeV}$$

PEW constraints imply heavy charged scalars



LIP Mass ~ 75 - 80 GeV

-  Direct detection limits
-  LEP direct searches
-  Vacuum stability
-  Perturbativity
-  DM relic density

- For heavy-Higgs scenarios, with  $m_h = 500$  GeV, it is also possible to obtain an appropriate LIP relic density.
- Other viable regions of parameter space exist, but don't lead to interesting collider phenomenology.

# Detection Prospects at LHC

There are many ways in which one may detect the presence of an additional, inert doublet at the LHC. These include:

- The modification of the total width  $\Gamma_h$  of the Higgs boson.  
(Barbieri, Hall, Rychkov 2006; Cao, Ma, Rajasekaran, 2007)
- Direct signals of the inert scalars  $A, H^\pm$  via their decays to SM particles +  $S$ .

**The cleanest signatures come from final states including multiple high- $p_T$  charged leptons and substantial missing transverse energy:**

1 Dilepton Channel:  $pp \longrightarrow \ell^+ \ell^- + \cancel{E}_T$

(Initial discovery process at LHC)

2 Trilepton Channel:  $pp \longrightarrow \ell^+ \ell^- \ell^\pm + \cancel{E}_T$

(Additional evidence for IDM, further information about the scalar mass spectrum)

**It's also important to note that...**

... while the results we discuss here are presented in the context of the IDM, they also apply in a wide variety of other scenarios in which a scalar WIMP makes up the majority of the dark-matter.

# Benchmark Scenarios for Collider Phenomenology

Satisfy all applicable constraints and reproduce the WMAP DM abundance within  $3\sigma$  range.

	Benchmark	$m_h$ (GeV)	$m_S$ (GeV)	$\delta_1$ (GeV)	$\delta_2$ (GeV)	$\lambda_L$
Light Higgs	LH1	150	40	100	100	-0.275
	LH2	120	40	70	70	-0.15
	LH3	120	82	50	50	-0.20
	LH4	120	73	10	50	0.0
	LH5	120	79	50	10	-0.18
Heavy Higgs	HH1	500	76	250	100	0.0
	HH2	500	76	225	70	0.0
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- **LH1, HH1:**  $\delta_2 > M_Z$  (on-shell  $A \rightarrow SZ$  decay).



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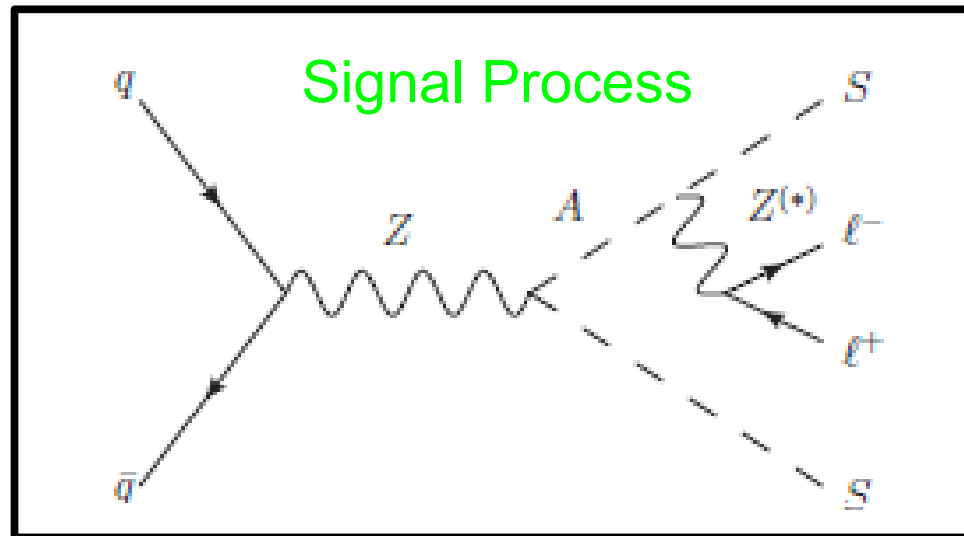
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- **LH5, HH3:**  $\delta_2 \lesssim 40$  GeV; off-shell  $A$  decay, very soft leptons.
- **LH4** small  $\delta_1$ ;  $H^\pm A \rightarrow \ell^+\ell^-\ell^\pm + \cancel{E}_T$  with soft  $\ell^\pm$  contributes.

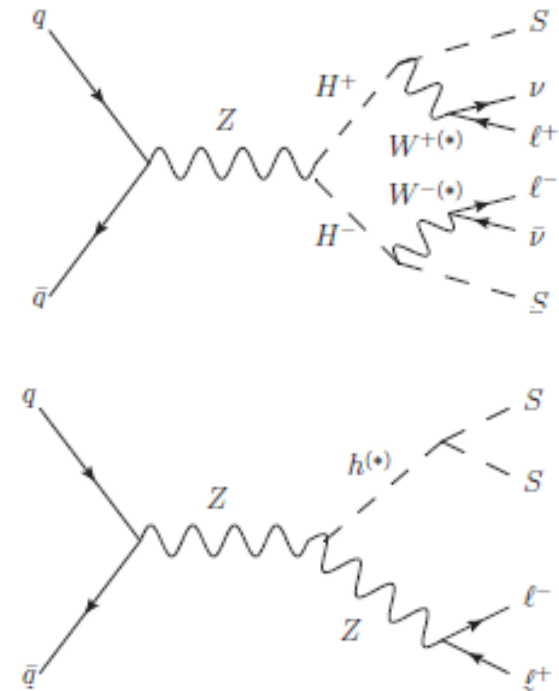
# Dilepton Channel: Signals

A number of processes contribute to

$$pp \rightarrow \ell^+ \ell^- + \cancel{E}_T \text{ in the IDM:}$$



SA Pair-Production

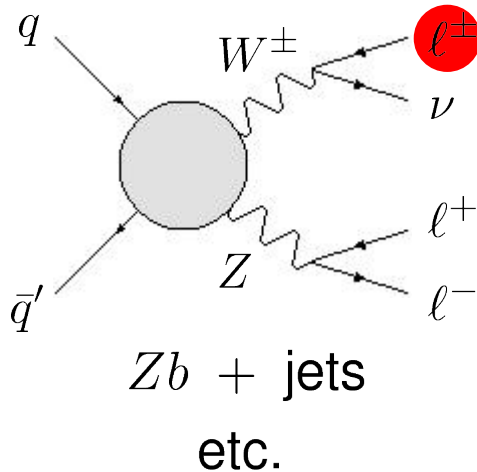
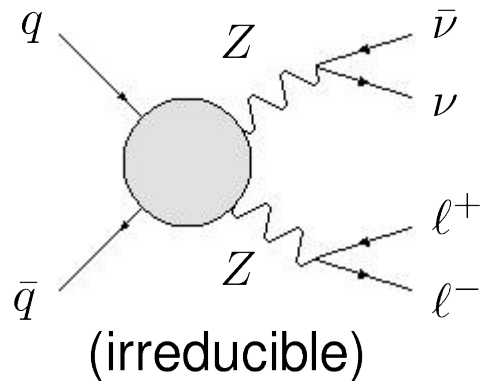


Model-Dependent Backgrounds

# Standard-Model Backgrounds

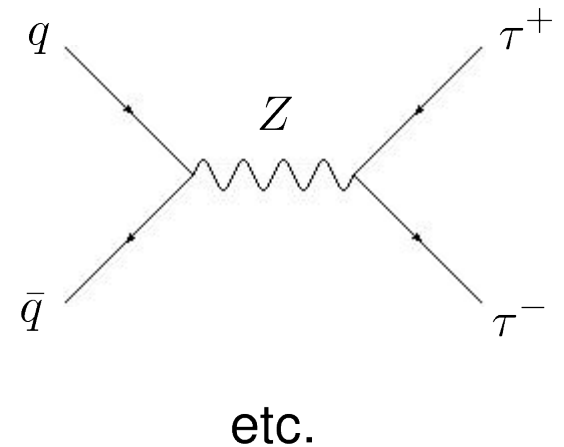
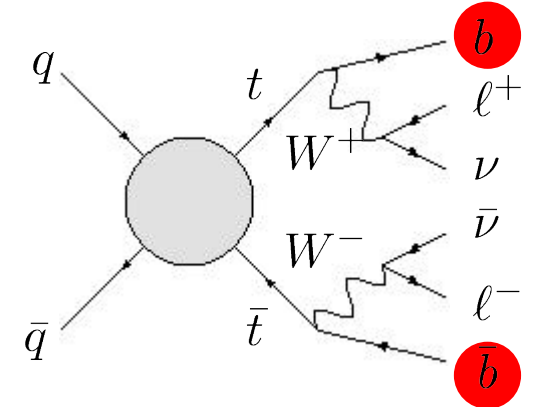
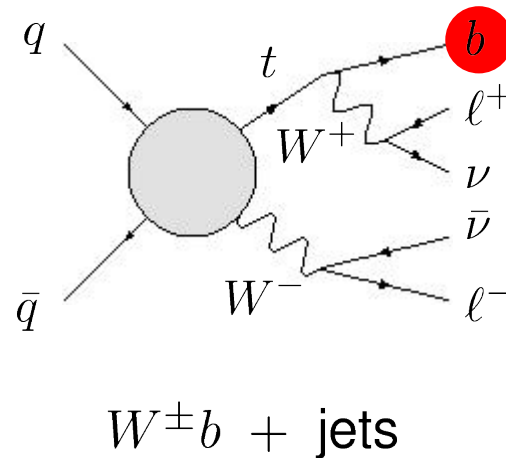
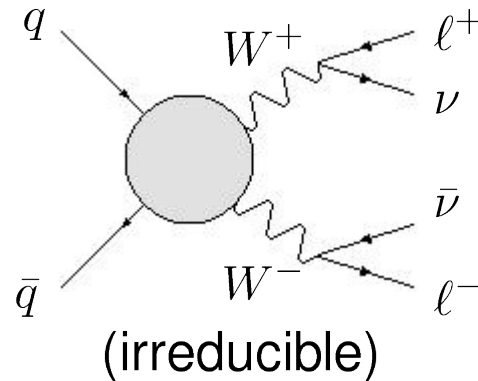
## “Z-Type”

( $M_{\ell\ell}$  peaked around Z-pole)



## “W-Type”

(broad  $M_{\ell\ell}$  distribution)



# Event Selection

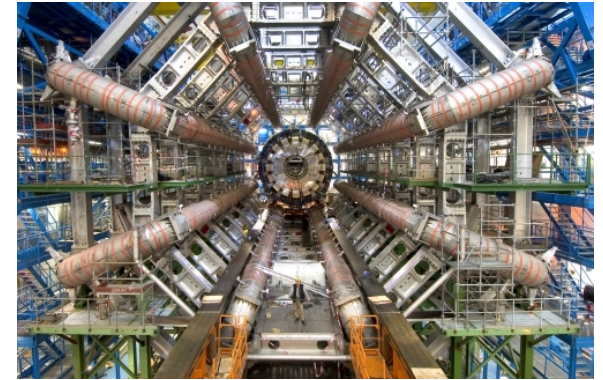
## Level I: Detector Acceptance Cuts

- Exactly two SFOS leptons ( $e$  or  $\mu$ ).
- $p_{T\ell} \geq 15$  GeV,  $|\eta_\ell| < 2.5$  for each lepton.
- Lepton isolation:  $\Delta R_{\ell\ell} \geq 0.4$  for lepton pair,  $\Delta R_{\ell j} \geq 0.4$  for each possible jet-lepton pairing.

$\Delta R_{\ell\ell}$  resolution limit crucial for small  $\delta_2$ !

## Level II: Universal Background Suppression Cuts

- $\cancel{E}_T \geq 30$  GeV.
- Jet veto: no jet with both  $p_{Tj} > 20$  GeV and  $|\eta_j| < 3.0$ .



- Basic cuts designed to mimic realistic LHC detector acceptance.



- Substantial reduction in  $Wt$ ,  $t\bar{t}$ ,  $W + \text{jets}$ .
- Effective elimination of Drell-Yan  $\tau\tau$  BG.

# Event Selection



## Level III: Optimization Cuts

- Angular-separation cuts:

- $\cos \phi_{\ell\ell} \geq \cos \phi_{\ell\ell}^{\min}$
- $\Delta R_{\ell\ell} \leq \Delta R_{\ell\ell}^{\max}$

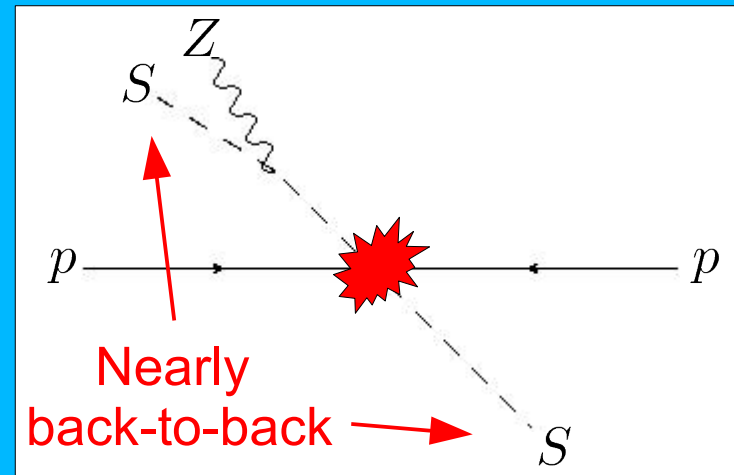
Useful for  $\delta_2 < M_Z$

$$H_T \equiv \sum_{i=1}^2 p_{T\ell}^i + \cancel{E}_T$$

- Invariant mass cut:  $M_{\ell\ell}^{\min} \leq M_{\ell\ell} \leq M_{\ell\ell}^{\max}$ .
- Minimum total transverse momentum  $H_T$  for each event:  $H_T \geq H_T^{\min}$ .
- Elevated thresholds for missing transverse energy:  $\cancel{E}_T \geq \cancel{E}_T^{\min} > 30 \text{ GeV}$ .
- Maximum lepton  $p_T$ :  $p_{T\ell} \leq p_{T\ell}^{\max}$ .

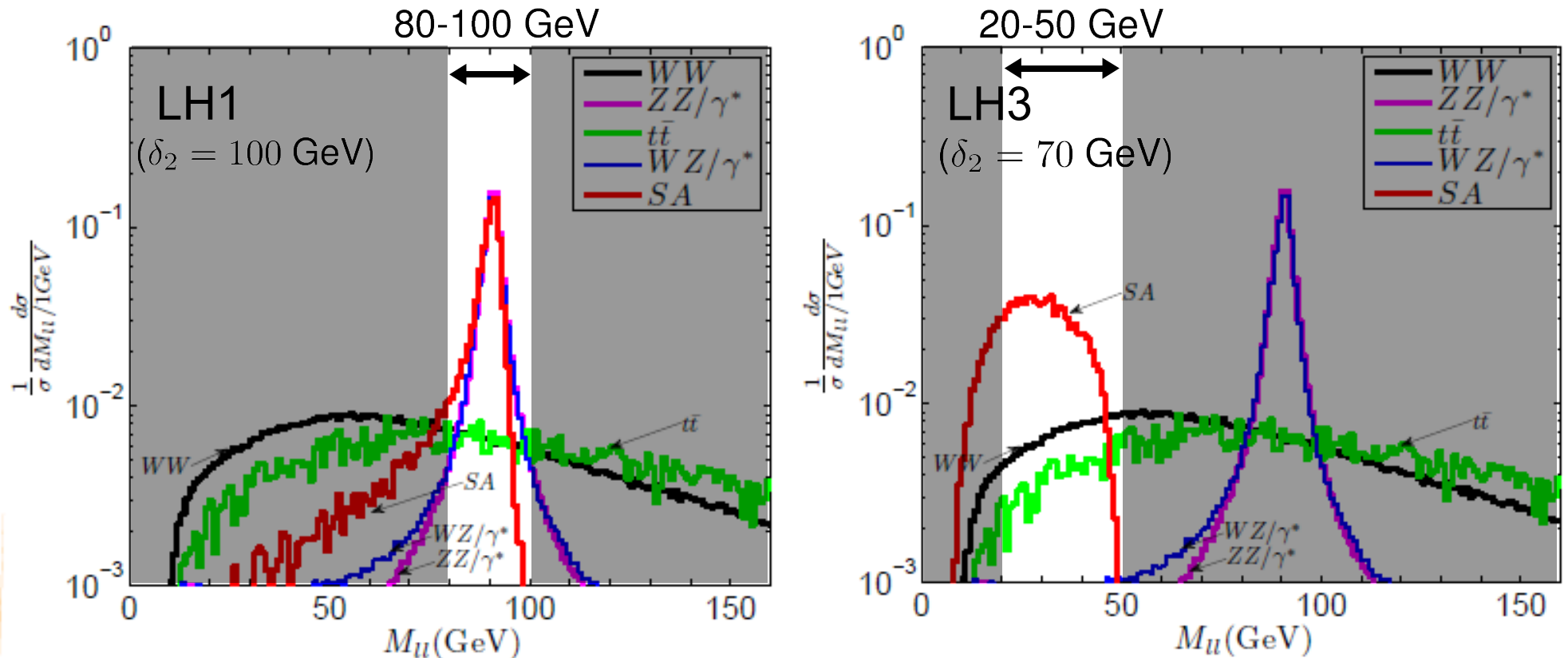
Useful when  $\delta_2$  is small and  $\ell^\pm$  quite soft.

Not a terribly powerful discriminant:  $\cancel{E}_T$  contributions from the LIPs largely cancel.





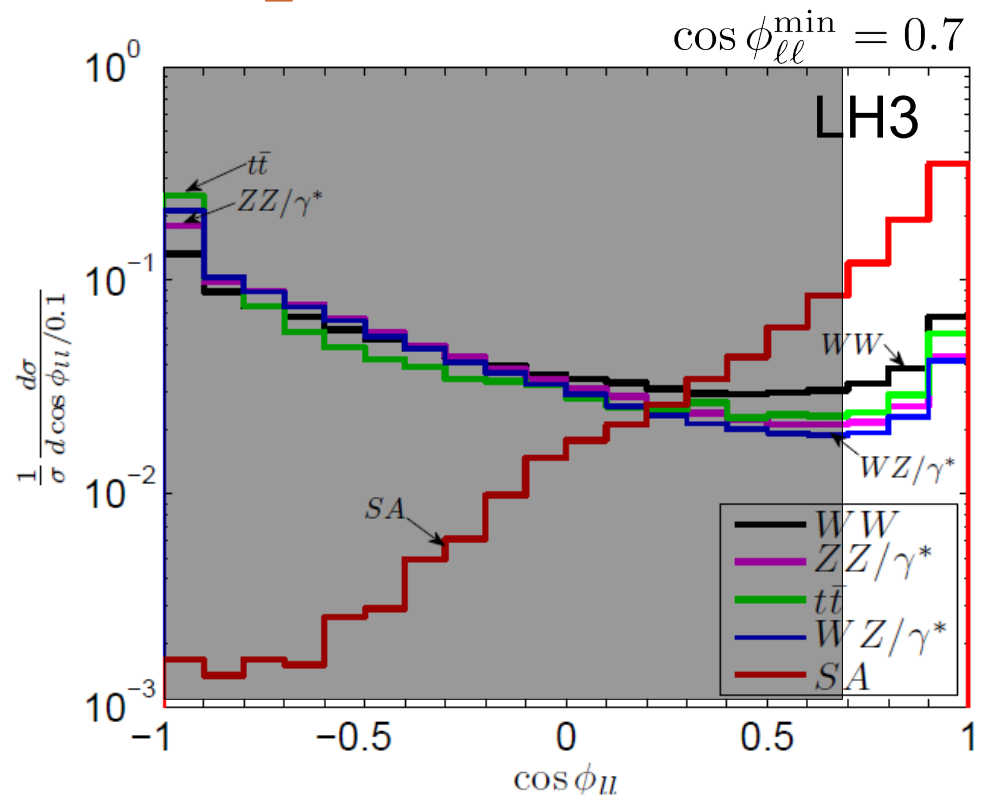
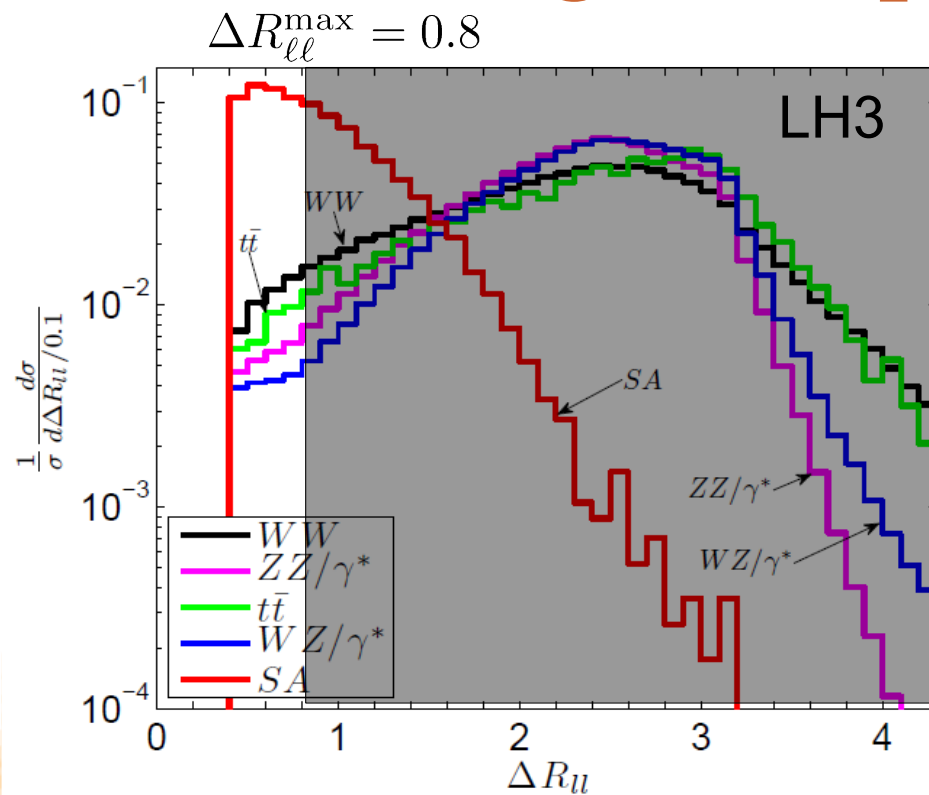
# Invariant Mass Distributions



- When  $\delta_2 > M_Z$  and  $A$  decays are on shell,  $t\bar{t}$ ,  $WW$  backgrounds can be substantially reduced by a cut on  $M_{\ell\ell}$ .
- When  $\delta_2 < M_Z$  and  $A$  decays are off shell,  $WZ/\gamma^*$  and  $ZZ/\gamma^*$  can be effectively eliminated by a  $Z$  veto.

Note: all distributions  
Normalized to one!

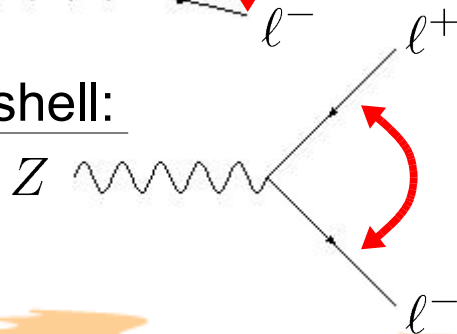
# Charged-Lepton Separation



Off shell:



On shell:



- When  $\delta_2 < M_Z$ , the charged leptons from  $A$  decay are more collinear and less energetic than those from on-shell  $Z$ -decays.
- This allows us to further reduce SM BGs via cuts on angular variables: e.g.  $\cos \phi_{\ell\ell}$  and  $\Delta R_{\ell\ell}$ .

# Results

## Best Discovery Prospects:

### Light Higgs

(LIP accounts for DM relic abundance)

Benchmark	$S/B$	$S/\sqrt{B}$
LH1	0.04	3.87
LH2	1.53	11.66
LH3	0.52	3.04
LH4	0.57	3.29
LH5	0.02	0.02
HH1	0.03	1.42
HH2	0.56	4.55
HH3	0.04	2.12

( $\sqrt{s} = 14 \text{ TeV}$ ,  $\mathcal{L} = 100 \text{ fb}^{-1}$ )

- **LH2** ( $\delta_2 = 70 \text{ GeV}$ ,  $m_S = 40 \text{ GeV}$ ):  
Large  $\sigma_{SA}$  due to light scalars.  $A$  decays off-shell, making angular cuts efficient.

Dramatic signal!

### Heavy Higgs

(DM relic abundance and improved naturalness!)

- **HH2** ( $\delta_2 = 70 \text{ GeV}$ ,  $m_S = 76 \text{ GeV}$ ):  
Similar to LH2.  $\sigma_{SA}$  lower due to heavier scalars, but angular cuts still effective.

# Results

## Light Scalars, On-Shell Decay:

### Light Higgs

(LIP accounts for DM relic abundance)

Benchmark	$S/B$	$S/\sqrt{B}$
LH1	0.04	3.87
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( $\sqrt{s} = 14 \text{ TeV}$ ,  $\mathcal{L} = 100 \text{ fb}^{-1}$ )

- **LH1** ( $\delta_2 = 100 \text{ GeV}$ ,  $m_S = 40 \text{ GeV}$ ):  
Large  $\sigma_{SA}$ , but  $A$  decays off-shell and  $ZZ/\gamma^*$ ,  $WZ$  BGs hard to eliminate. Good discovery prospects nevertheless.

### Heavy Higgs

(DM relic abundance and improved naturalness!)

- **HH1** ( $\delta_2 = 100 \text{ GeV}$ ,  $m_S = 76 \text{ GeV}$ ):  
Similar to LH1:  $A$  decays off-shell  $ZZ/\gamma^*$ ,  $WZ$  BGs again hard to eliminate. Signal difficult to resolve at  $\mathcal{L} = 100 \text{ fb}^{-1}$ .

# Results

## Heavier Scalars, Off-Shell Decay:

### Light Higgs

(LIP accounts for DM relic abundance)

- **LH3, LH4** ( $\delta_2 = 50$  GeV,  $m_S \sim 80$  GeV):  $\sigma_{SA}$  smaller due to heavier LIP. LH4 significance augmented by  $pp \rightarrow H^\pm A$  contribution where  $\ell^\pm$  from  $H^\pm$  decay is soft.
- **LH5** ( $\delta_2 = 10$  GeV,  $m_S \sim 80$  GeV): Leptons too soft to detect, due to small  $\delta_2$ .

### Heavy Higgs

(DM relic abundance and improved naturalness!)

- **HH3** ( $\delta_2 = 30$  GeV,  $m_S = 76$  GeV):  $M_{\ell\ell}$  cut effective, but surviving BGs have similar  $\cos \phi_{\ell\ell}$ ,  $\Delta R_{\ell\ell}$  to signal.

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LH5	0.02	0.02
HH1	0.03	1.42
HH2	0.56	4.55
HH3	0.04	2.12

( $\sqrt{s} = 14$  TeV,  $\mathcal{L} = 100 \text{ fb}^{-1}$ )

**... and from this, we learn:**

The best prospects for detection in the dilepton channel are obtained for a light Higgs boson ( $m_h \sim 114 - 180$  GeV) and:

$$40 \text{ GeV} \lesssim \delta_2 \lesssim 80 \text{ GeV} \quad m_S \sim 40 \text{ GeV}$$

with a statistical significance as high as  $\sim 10\sigma$ .

**... but also (and perhaps even more importantly):**

It is possible for the IDM to explain the observed dark-matter abundance, provide the necessary  $S$  and  $T$  contributions to correct for a heavy Higgs, and at the same time yield visible signals in the dilepton channel at the LHC!

## The Most Relevant Processes:

# Analysis: Trilepton Channel

- One can also look for signatures of the inert doublet model in the trilepton channel.
- Analysis similar to SUSY trilepton searches.

Principal signal process

Occurs only when  $\delta_1 > \delta_2$   
(significant for  $\delta_1 > \delta_2 + M_W$ ).

- To examine this effect, three new benchmark points added:

Benchmark	$m_h$ (GeV)	$m_S$ (GeV)	$\delta_1$ (GeV)	$\delta_2$ (GeV)	$\lambda_L$
LH6	130	40	100	70	-0.18
LH7	117	37	70	100	-0.14
LH8	120	78	70	35	-0.18



# Event Selection

## Level I + II

- Exactly three charged leptons ( $e$  or  $\mu$ ), including at least one SFOS pair.
- $\cancel{E}_T \geq 50$  GeV in order to reduce backgrounds from heavy-flavor processes, etc.
- Otherwise, same as for dilepton channel.

## Level III

- Also include a cut on the transverse mass variable

$$M_{TW} \equiv (E_{\ell_W} + \cancel{E}_T)^2 - (\vec{p}_{\ell_W} + \vec{p}_T)^2.$$

Dominant Backgrounds After Level I+II Cuts:

$$WZ \rightarrow \ell^+ \ell^- \ell^\pm + \cancel{E}_T$$

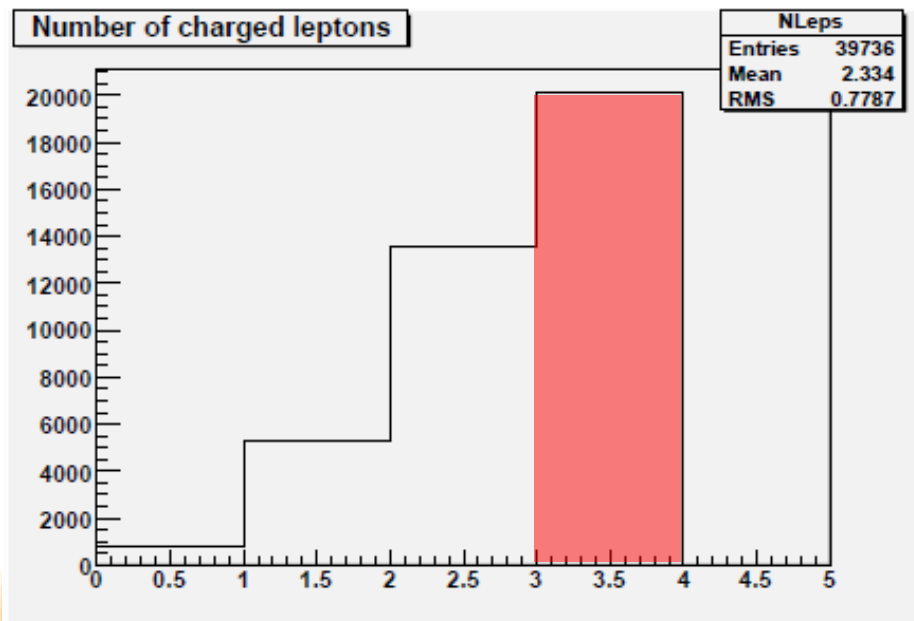
$$t\bar{t} \rightarrow \text{jets} + \ell^+ \ell^- \ell^\pm + \cancel{E}_T$$

(Soft)

# Problems with Soft Leptons

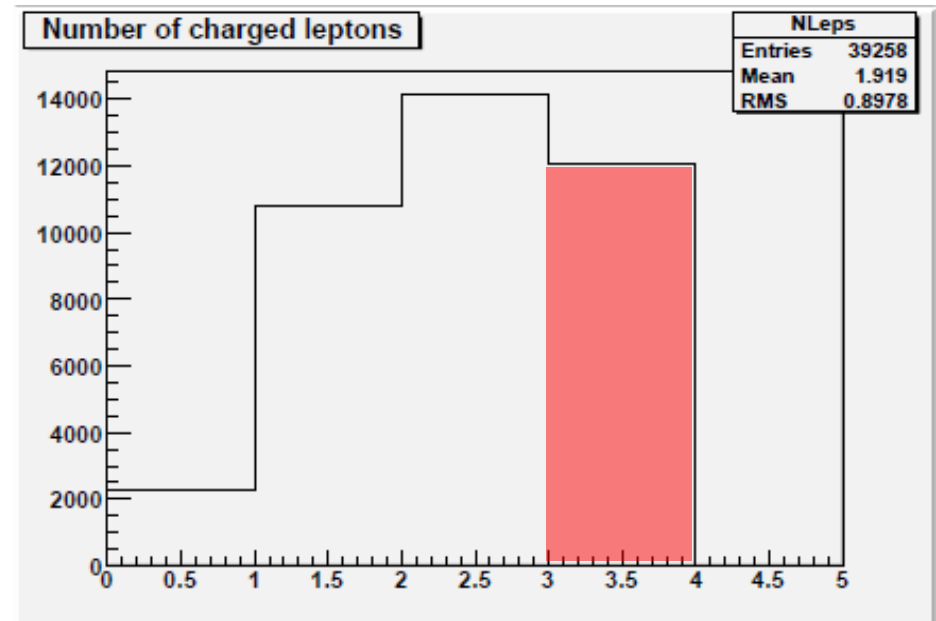
**LH1**

$(\delta_1 = \delta_2 = 100 \text{ GeV})$



**LH3**

$(\delta_1 = \delta_2 = 50 \text{ GeV})$



- When  $\delta_{1,2}$  drop below  $\sim 65 \text{ GeV}$ , one or more of the leptons often has extremely low  $p_T$  and escapes detection.

# Trilepton Channel Results

[arXiv:1005.0090]

Benchmark				
	$\sigma_{H\pm A}$ (fb)	$\sigma_{BG}^{comb}$ (fb)	$S/B$	$S/\sqrt{B}$ (300 fb <sup>-1</sup> )
LH1	0.038	0.191	0.20	2.15
<u>LH2</u>	0.078	0.114	0.68	5.64
LH3	0.035	0.131	0.27	2.36
<u>LH6</u>	0.101	0.221	0.46	5.27
LH7	0.270	7.259	0.04	2.45
LH8	0.031	0.591	0.05	1.00

**5 $\sigma$  discovery in  
both dilepton &  
trilepton  
channels!**

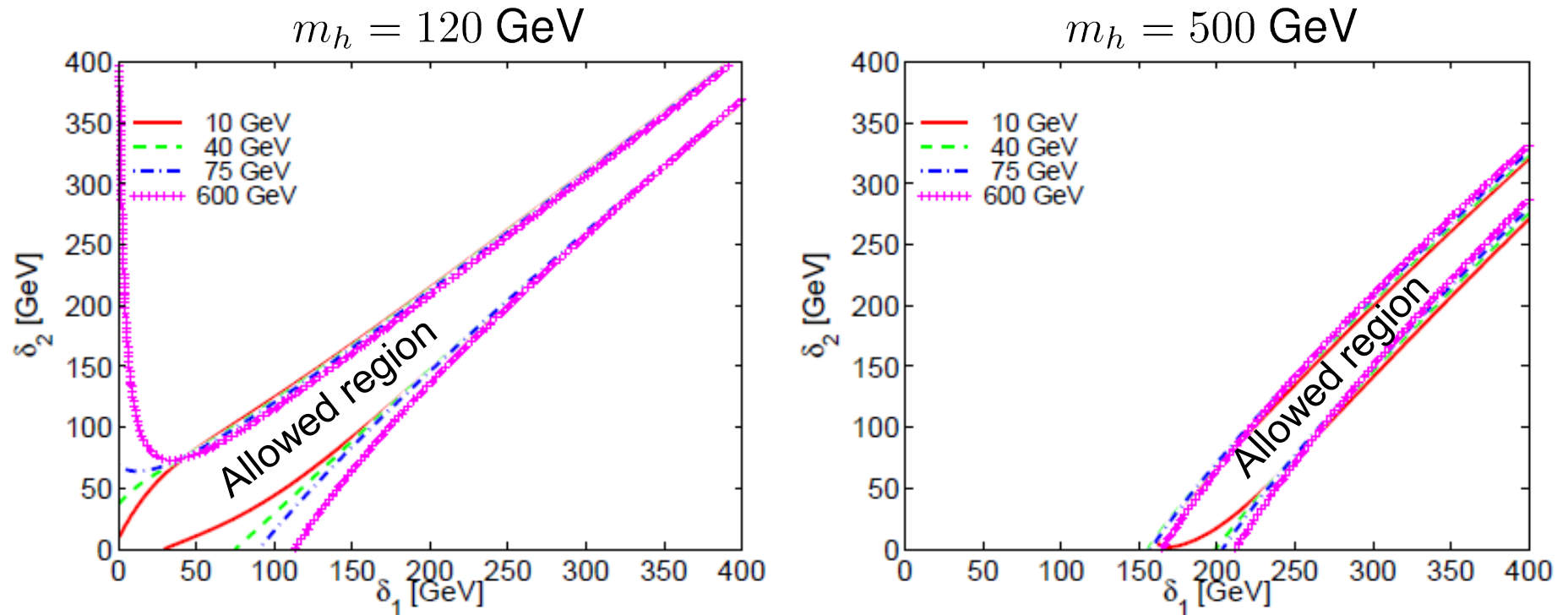
- The discovery prospects in the trilepton channel aren't as good as in the dilepton channel, and higher integrated luminosity is generally required.
- Nevertheless, 5 $\sigma$  evidence can be obtained when  $m_s \sim 40$  GeV and  $65 \text{ GeV} \lesssim \delta_{1,2} \lesssim 80 \text{ GeV}$ .
- For smaller  $\delta_{1,2}$ , leptons tend to be soft, and often escape detection.

# Summary and Conclusions

- The IDM is a simple and versatile model, capable of...
  - explaining the composition and observed relic density of dark matter in the universe.
  - Rendering a heavy Higgs boson with  $m_h \sim 400 - 600$  GeV consistent with PEW constraints.
  - much more.
- There are **several** parameter-space regimes in which the model reproduces the WMAP DM density. Most feature a light LIP, with  $m_S \lesssim 80$  GeV.
- In many of these scenarios, a **striking signal** should be observable at the LHC in the dilepton channel. Corroborating evidence may also be obtainable in the trilepton channel for models with a light LIP and  $65 \text{ GeV} \lesssim \delta_2 < M_Z$ .

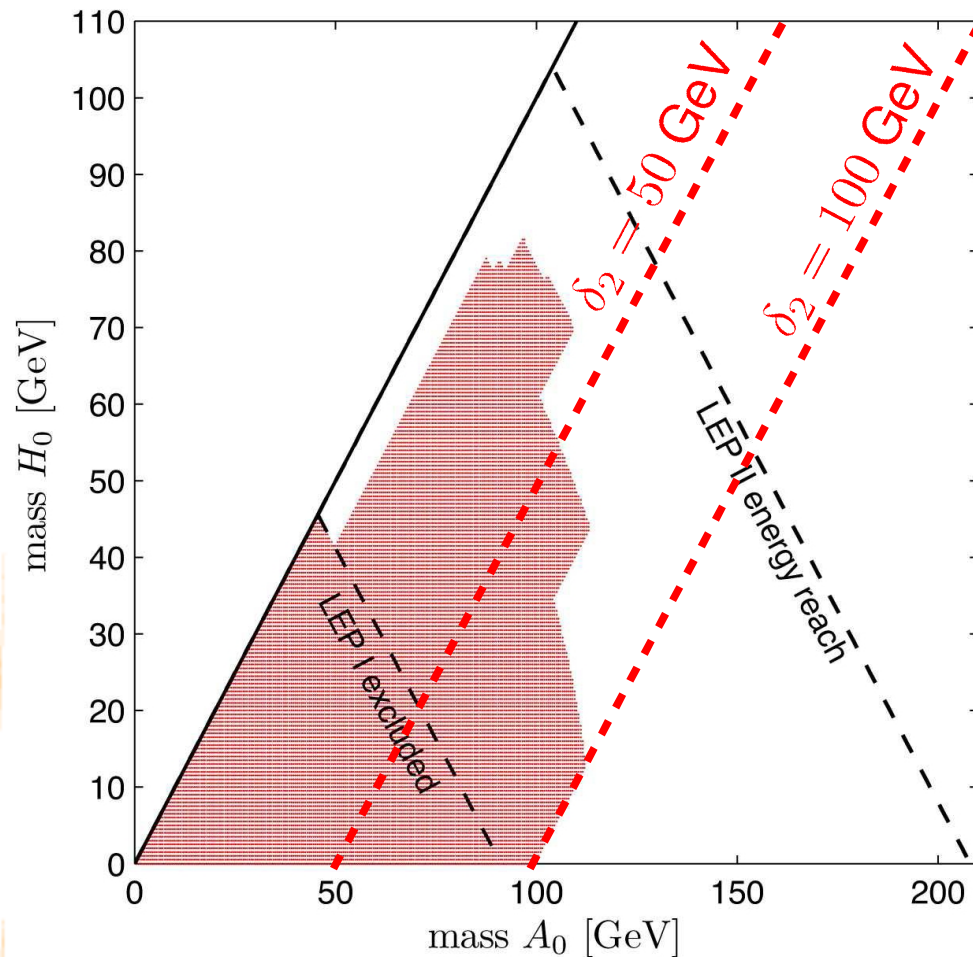
# Extra Slides

# Constraints from EW Precision Tests



- For a light Higgs, no net shift in  $S, T$  is needed. Electroweak precision constraints therefore require  $\delta_1 \sim \delta_2$ .
- To provide the necessary  $\Delta T$  contribution to allow for a heavy Higgs, the contour shifts to a region of parameter space where  $\delta_1 > \delta_2$ .

# LEP II Bounds: Direct Detection Limits



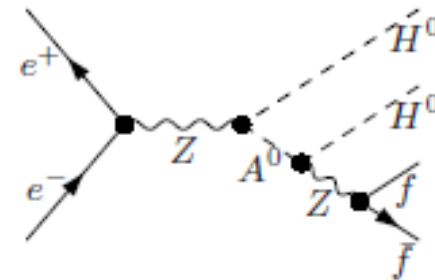
■ Excluded by LEP data

- The IDM is constrained by LEP bounds on cross-sections for

- $(e^+e^- \rightarrow \ell^+\ell^- + \cancel{E}_T)$
- $(e^+e^- \rightarrow jj + \cancel{E}_T)$

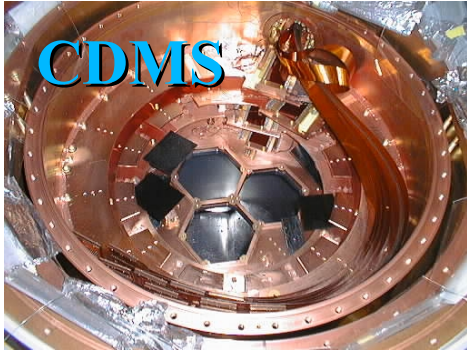
with acollinear jets.

(Lundström, Gustaffson, Edsjö 2008)



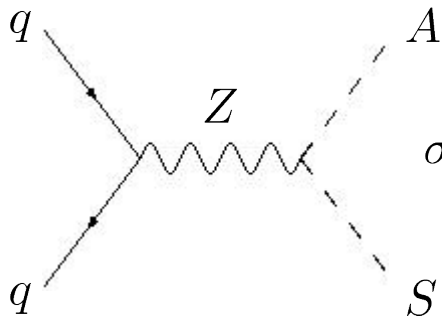
- LEP data favor large splittings, ( $\delta_2 \gtrsim 50 - 100$  GeV) or a heavy LIP ( $m_s \gtrsim 75$  GeV).





# Direct Detection

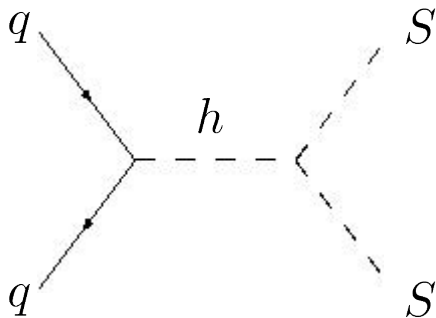
Z-exchange (spin-independent)



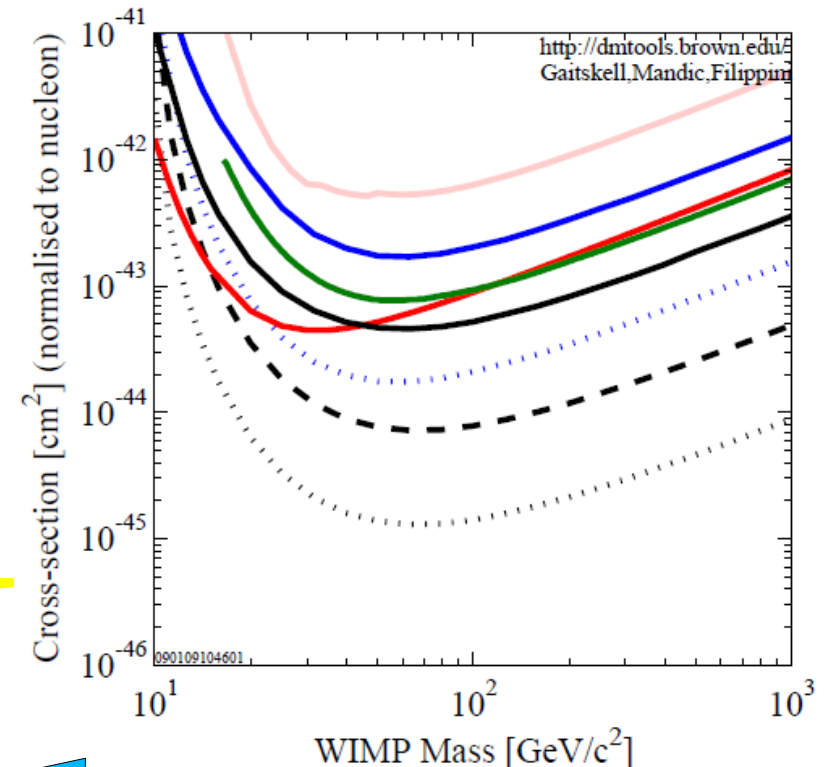
$$\sigma = \frac{G_F^2 m_r^2}{2\pi} [N - (1 - 4s_W^2)Z]^2$$

**Too large by a factor of  $\sim 10^9$  !**  
(Consequently,  $\delta_2 \gtrsim 500$  keV)

h-exchange (spin-independent)



$$\sigma = \frac{1}{4\pi} \left( \frac{m_N m_r}{m_S} \right)^2 \left( \frac{\lambda_L f}{m_h^2} \right)^2$$



DATA listed top to bottom on plot  
 CRESST 2007 60 kg-day CaWO<sub>4</sub>  
 CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)  
 ZEPLIN III (Dec 2008) result  
 CDMS: 2004+2005 (reanalysis) +2008 Ge  
 XENON10 2007 (Net 136 kg-d)  
 CDMS Soudan 2007 projected  
 SuperCDMS (Projected) 2-ST@Soudan  
 SuperCDMS (Projected) 25kg (7-ST@Snolab)